Online appendix A.

Description of supplemental location and smoothing methodologies.

1. **Supplemental location methodology.**

After much experimentation, a somewhat involved multi-step procedure was used approach was used to determine 20 supplemental locations. The procedure was as follows, repeated independently for each month of the year:

(a) *Read analysis data and terrain height data*. 2002-2013 1/8-degree analyzed precipitation data was read in for that month and for the surrounding two months as well as terrain heights on the same grid.

(b) *Determine the climatological distribution of analyzed events*. The precipitation amounts associated with a large number of percentiles of the cumulative distribution were determined for each grid point, i.e., the quantiles of the cumulative distribution. For the grid point (i, j), the cumulative precipitation amount associated with the percentile p was denoted by $A_p(i, j)$.

(b) *Determine terrain characteristics*. Using the gridded 1/8-degree terrain heights, at each grid point in the CONUS, the terrain height $h(i,j)$ and east-west and north-south height gradients $dh(i,j)/dx$ and $dh(i,j)/dy$ were calculated. The gradients were based on a centered difference using the neighboring points.

(c) *Determine a standard deviation of terrain characteristics using surrounding values*. In the subsequent step we form a penalty function that includes terms for the locational differences in analysis climatology, terrain height, and terrain gradient differences. We'd prefer these to be similar in magnitude for ease of interpretation and analysis. To achieve this, for each grid point, the standard deviation of terrain heights and gradients in a surrounding neighborhood were calculated. Let $S = [(i,j)_1, \ldots, (i,j)_N]$ be the set of N grid points in a box of +/- 10 CONUS land grid points around the analysis grid point (i, j). Then the local sample standard deviation for terrain height was calculated as

$$\sigma[h(i,j)] = \left(\frac{1}{N-1}\sum_{k=1}^{N}\left(h(i,j) - \overline{h(i,j)}\right)^2\right)^{1/2}, \qquad \text{(A1)}$$

where the overbar indicates the mean terrain height calculated over the same set of samples. Standard deviations for the gradients $\sigma[dh(i,j)/dx]$ and $\sigma[dh(i,j)/dy]$ were calculated in a similar manner.

(d) *Assign a penalty for the differences between locations in analyzed and forecast characteristics and distance*. Let $L(i, j, i_s, j_s)$ represent a penalty function that quantifies the difference between analyses and forecasts at grid point location (i, j) and potential supplemental location (i_s, j_s). The penalty function was of the form

$$L(i,j,i_s,j_s) = \alpha L_a(i,j,i_s,j_s) + \beta L_h(i,j,i_s,j_s)$$
$$+ \gamma L_{dhdx}(i,j,i_s,j_s) + \delta L_{dhdy}(i,j,i_s,j_s) + \epsilon L_d(i,j,i_s,j_s). \qquad \text{(A2)}$$

where L_a represents the penalty due to differences between analysis climatologies at the two locations. L_h, L_{dhdx}, and L_{dhdy} are scaled differences in terrain height and terrain gradients between the two locations, and L_d is a distance penalty. The four user-chosen weighting coefficients α, β, γ, δ, and ϵ were set to 0.4, 0.2, 0.2, 0.2, and 0.05, respectively, after some experimentation.

The penalty for differences in analyzed climatologies between the two locations was calculated as follows. First, we identified a lower and upper precipitation amount bound for measuring the integrated average difference in precipitation amounts. The lower bound percentile, p_{low}, was the quantile of the analyzed CDF at (*i,j*) associated with the lowest non-zero amount. The upper-bound percentile, p_{hi}, was the amount associated with the 95th percentile of the analyzed CDF. If $p_{low} > p_{hi}$, $p_{hi} = p_{low}$. Specifically, then, the analysis penalty function was calculated as

$$L_a(i,j,i_s,j_s) = \int_{p_{low}}^{p_{hi}} \left|A_p(i,j) - A_p(i_s,j_s)\right| dp. \quad \text{(A3)}$$

A scaled penalty for the terrain height was calculated as

$$L_h(i,j,i_s,j_s) = \left|\frac{h(i,j)-h(i_s,j_s)}{\sigma[\,h(i,j)]}\right|, \quad \text{(A4)}$$

with $L_{dhdx}(i,j,i_s,j_s)$, and $L_{dhdy}(i,j,i_s,j_s)$ calculated similarly. Finally, the distance penalty function $L_d(i,j,i_s,j_s)$ was simply the Euclidean distance between (*i, j*) and (i_s,j_s) in units of grid points.

(e) *Choose the supplemental location and then exclude neighboring grid points from consideration*. If we were considering the first location, this was simply the grid point (*i, j*) itself. If it was the second or higher ordinal supplemental location, it was the grid point location with the smallest remaining penalty. After a given location was chosen, however, in order to make sure that supplemental locations were not too close to each other (so as to provide somewhat more independent data), the penalty function for every grid point with a Euclidean grid point distance of ≤ than 8 units was reassigned to an arbitrarily high value, effectively excluding the points from further consideration. Only grid points less than 80 grid units away from each other were evaluated with the loss function above.

Figure 1 in the main text showed supplemental locations and regression slopes and intercepts for the month of January. Figures A1 to A3 show similar plots but for April, July, and October.

2. **Smoothing Methodology.**

Probability forecasts from the analog method typically have some small-scale noise associated with them due to the choice of a different set of analog dates at adjacent grid points. In such a case, a spatially smoothed probability field might be desirable. However, sometimes probability differences at the grid scale can be somewhat meaningful, especially in the mountainous terrain of the western US. Hence, we seek a smoother with the following desirable qualities: (a) provide stronger smoothing in regions of flat terrain relative to regions with large terrain height variations; (b) provide a smoothing that does not unrealistically diminish the amplitude of coherent features, and (c) provide a realistic smoothing along coasts (analyzed data was not available offshore, so the raw probabilities are set to missing outside of the CONUS). Property (b) can be addressed in a relatively straightforward manner through the use of a Savitzky-Golay ("S-G" hereafter) smoothing algorithm, which is described in Press et al (1992, section 14.8). Here we will used a window size of 9 grid points and using a third-order polynomial, chosen after some experimentation (not shown).

Properties (a) and (c) were dealt with through somewhat more involved and ad-hoc procedures. To permit greater smoothing in areas with relatively flat terrain, we set the final probability field to a weighted combination of the raw probabilities and smooth probabilities, with the weights varying with terrain roughness. The terrain height file used in the GEFS system appropriate for global wavenumber 254 was used. At each ~ ½-degree forecast grid point, the local mean terrain height was determined for a 3x3 grid-point box centered on the box of interest. The standard deviation $\sigma_{i,j}^{T}$ for that 3x3 box was then calculated with respect to this mean value. A plot of the standard deviations are shown in Fig. A4. Finally, the weight $w_{i,j}$ to apply to the raw forecast was calculated as:

$$w_{i,j} = \begin{cases} 0.2 & \text{if } {\sigma_{i,j}^{T}}^{1/2} < 8 \\ 0.2 + \frac{\left({\sigma_{i,j}^{T}}^{1/2} - 8\right)}{16.66667} & \text{if } 8 \leq {\sigma_{i,j}^{T}}^{1/2} < 108 \\ 0.8 & \text{if } 108 \leq {\sigma_{i,j}^{T}}^{1/2} \end{cases} , \qquad \text{(A5)}$$

and the weight applied to the smooth forecast was 1- $w_{i,j}$. A map of the weight applied to the raw forecast is shown in Fig. A5.

Probability discontinuities along coastlines provided another challenge to getting reasonable results from the S-G smoother. Since analyzed data were available over the CONUS but not over adjacent water bodies, the resultant probability forecasts were only available over the CONUS. Hence, a spatial smoothing applied to this data field would produce unrealistic values along the coast. To deal with this, before the application of S-G smoothing, the water points were filled in with a weighted combination of probability data from nearby adjacent land areas. The approach to doing so was inspired by a simple objective analysis procedure akin to a single-pass Barnes analysis (Barnes, 1964). The probability assigned to a given ocean point consisted of a weighted combination of the probabilities from nearby land points. Define a length scale L=3 for the spatial weighting function, here defined in terms of number of grid points for simplicity. Define a cutoff radius R (=10 grid points). Then for a given ocean location (i, j), define S_L as the set of indices of all M CONUS land grid points within a cutoff radius distance of (i, j), $S_L = [(i, j)_1, \ldots, (i,j)_M]$. Assume there was also a set of associated distances $D_L=[D_1, \ldots, D_M]$ that provided the distance in grid points from (i, j). For the k*th* of M grid point locations, the distance-dependent weighting function w_k was calculated according to

$$w_k = e^{-D_k^2/L^2}, \tag{A6}$$

which was Gaussian in shape. Then the final smoothed probability value $p_{i,j}^s$ assigned to this location was

$$p_{i,j}^s = \frac{\sum_{k=1}^{M} w_k p_{(i,j)_k}}{\sum_{k=1}^{M} w_k} \quad , \tag{A7}$$

where $p_{(i,j)k}$ was the probability value at the k*th* of the M associated land locations within the cutoff radius. In the exceptional case where M=0, then $p_{i,j}^s$ was set to the average probability over the whole CONUS.

Below, Figs. A6 and A7 show sample probability forecasts before and after application of the S-G smoothing, respectively. As can be seen, most of the details such as in the high peaks of the Colorado Rockies were preserved, and over the flatter terrain the subsequent probabilities were smoother, but the relative amplitudes of probability maxima and minima were largely preserved.

Appendix A references:

Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, 1992: *Numerical Recipes in Fortran (2nd Ed.)*. Cambridge Press, 963 pp.

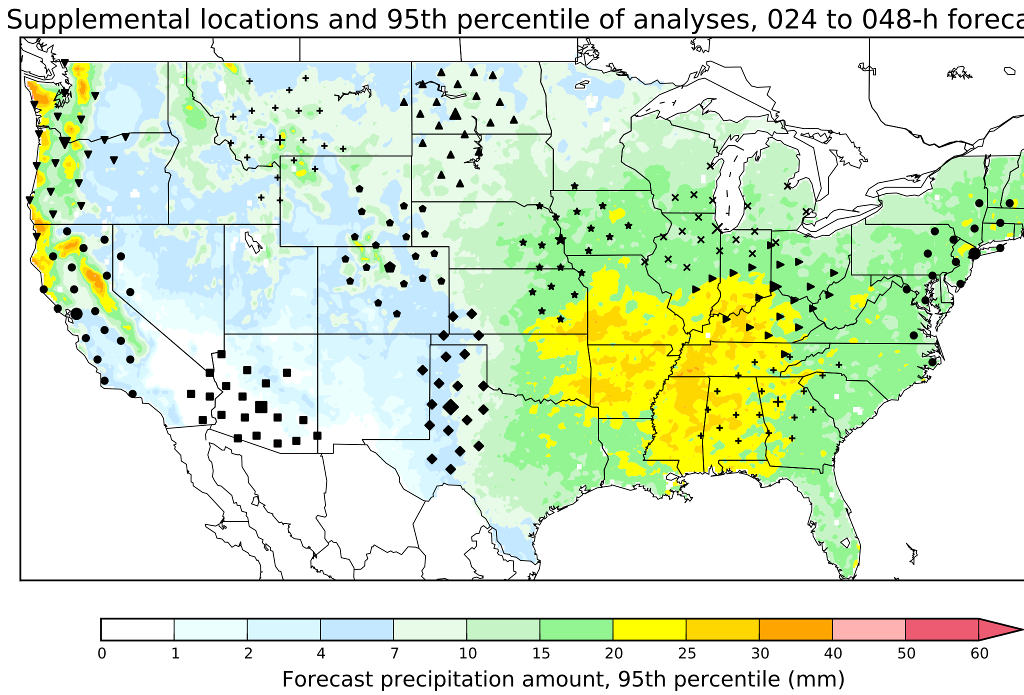

Figure A1: As in Fig. 1 from the article, but for the month of April.

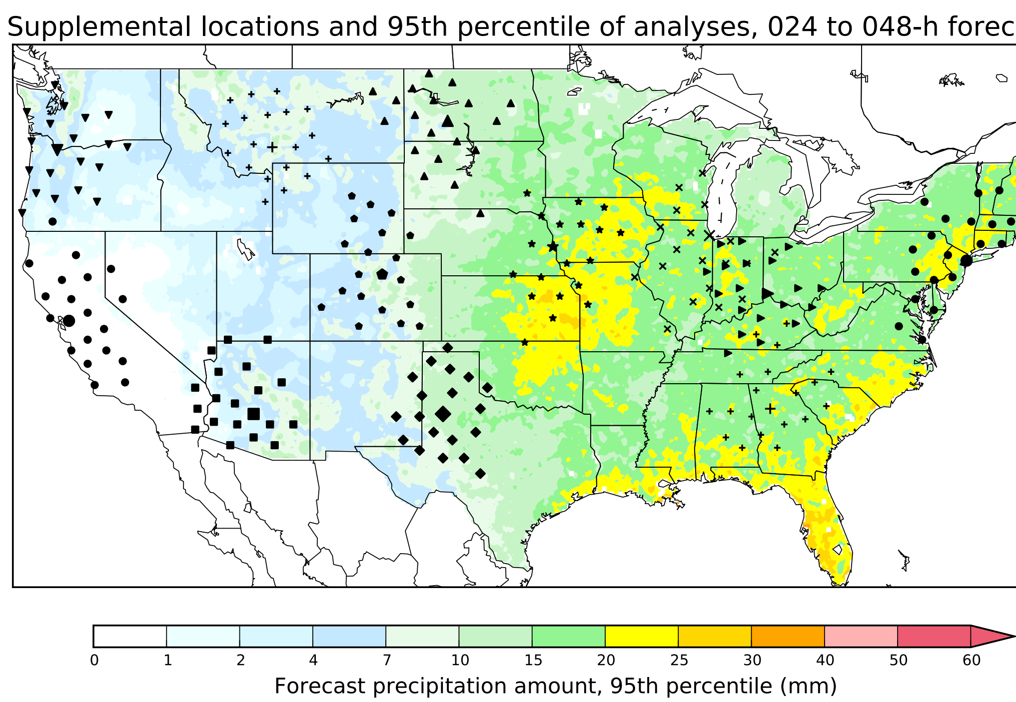

Figure A2: As in Fig. 1 from the article, but for the month of July.

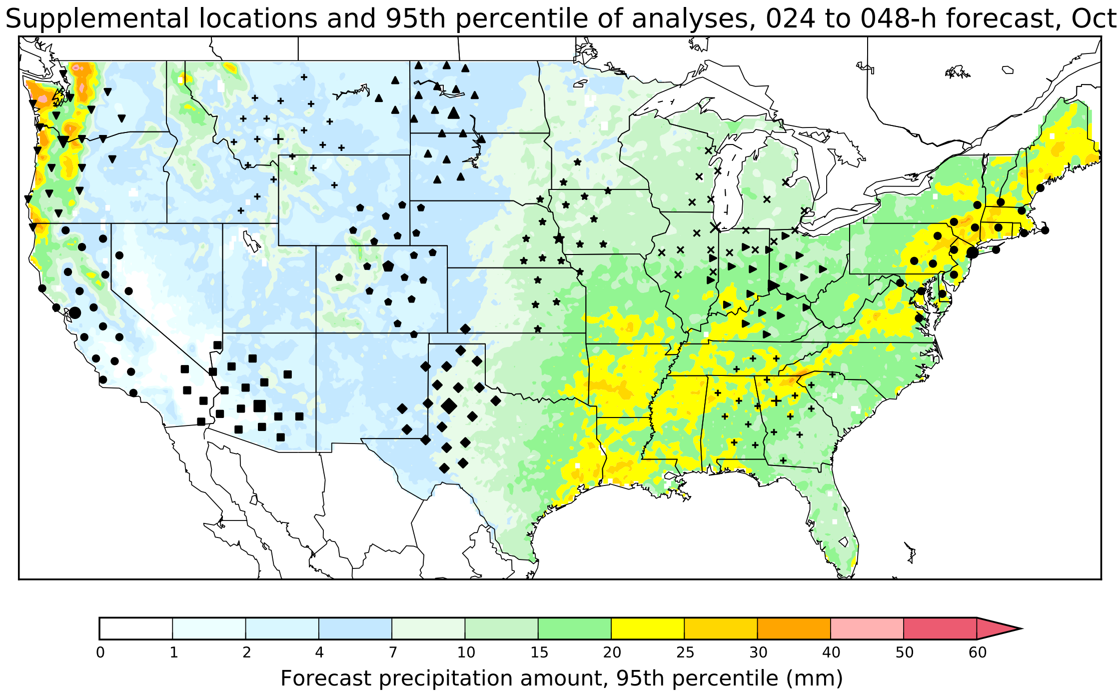

Figure A3: As in Fig. 1 from the article, but for the month of October.

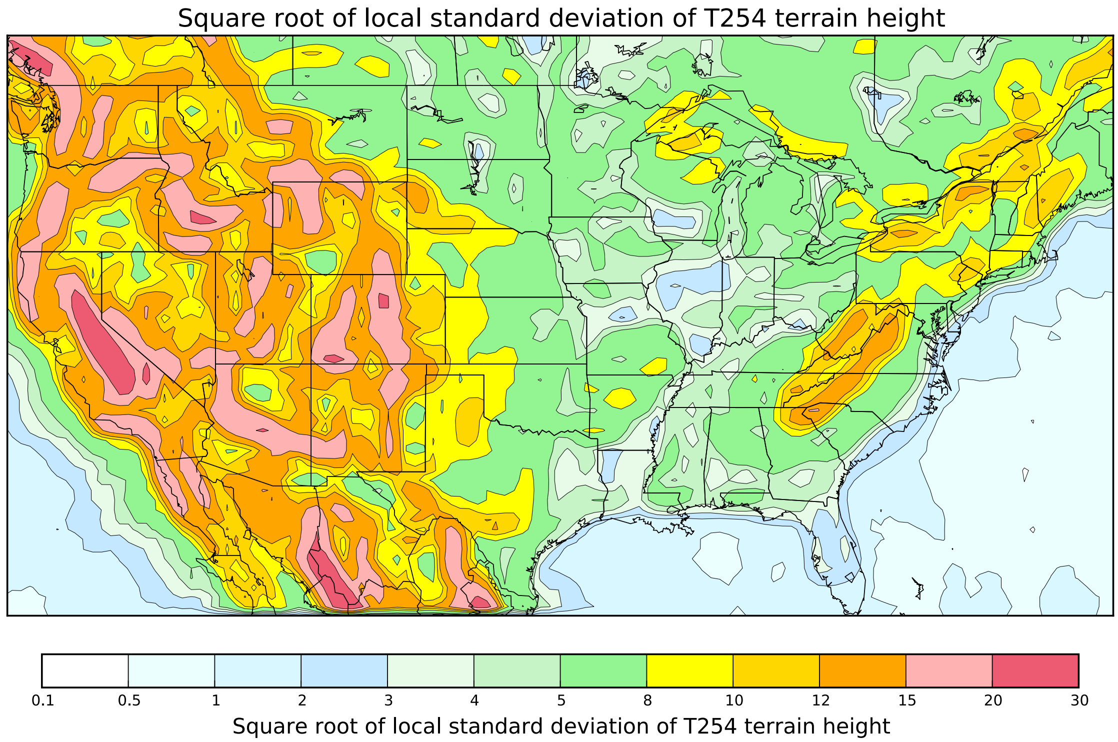

Figure A4: Map of the square root of the local standard deviation of T254 terrain height surrounding the CONUS.

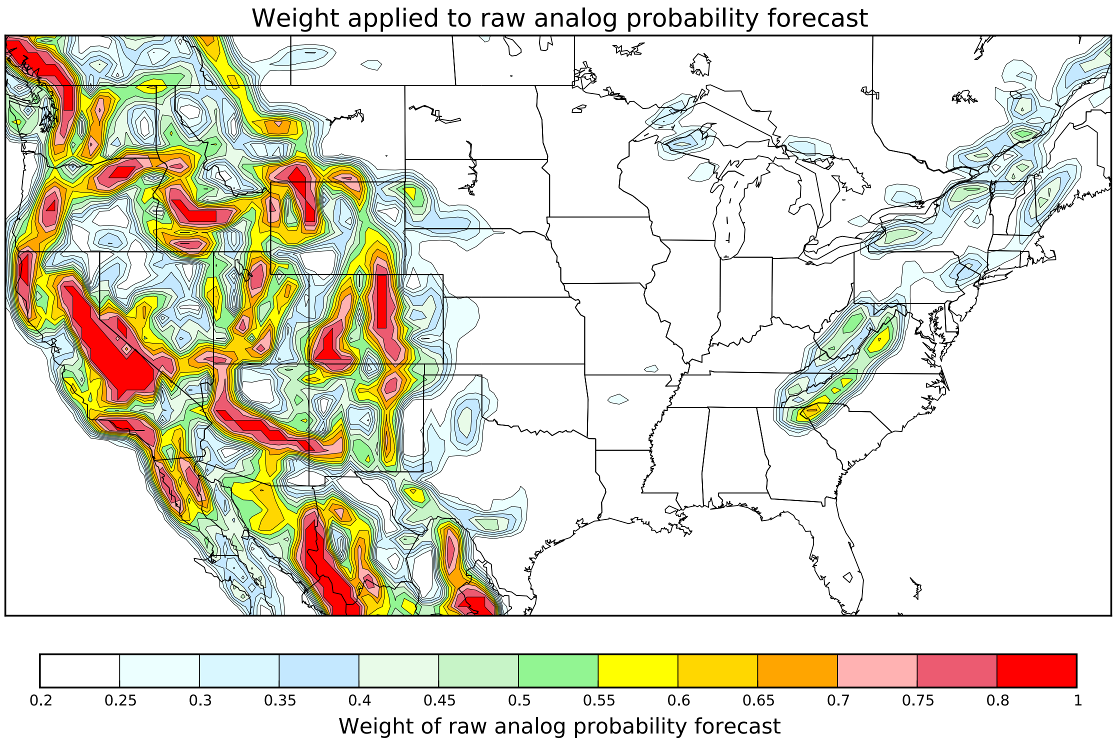

Figure A5: Weight applied to the raw ensemble forecasts. One minus this weight is applied to the Savitzky-Golay smoothed forecast.

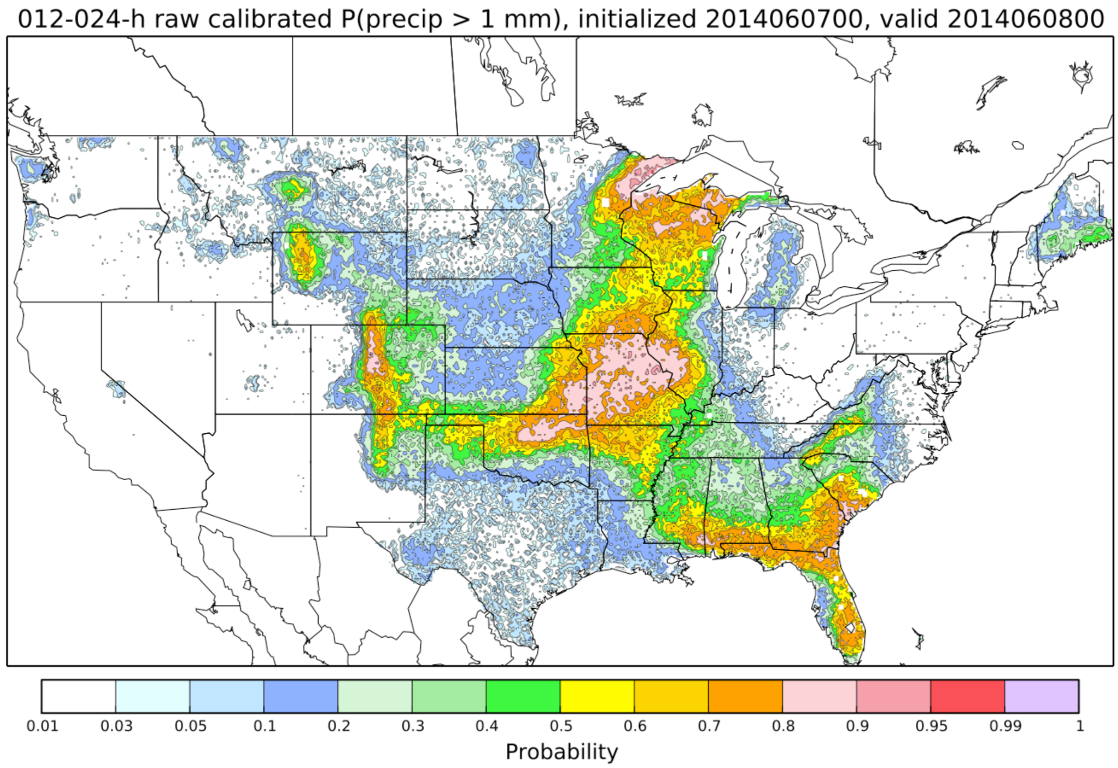

Figure A6: Example of unsmoothed probabilities produced by the analog procedure, in this case for 12-24 hour forecasts initialized at 00 UTC 7 June 2014.

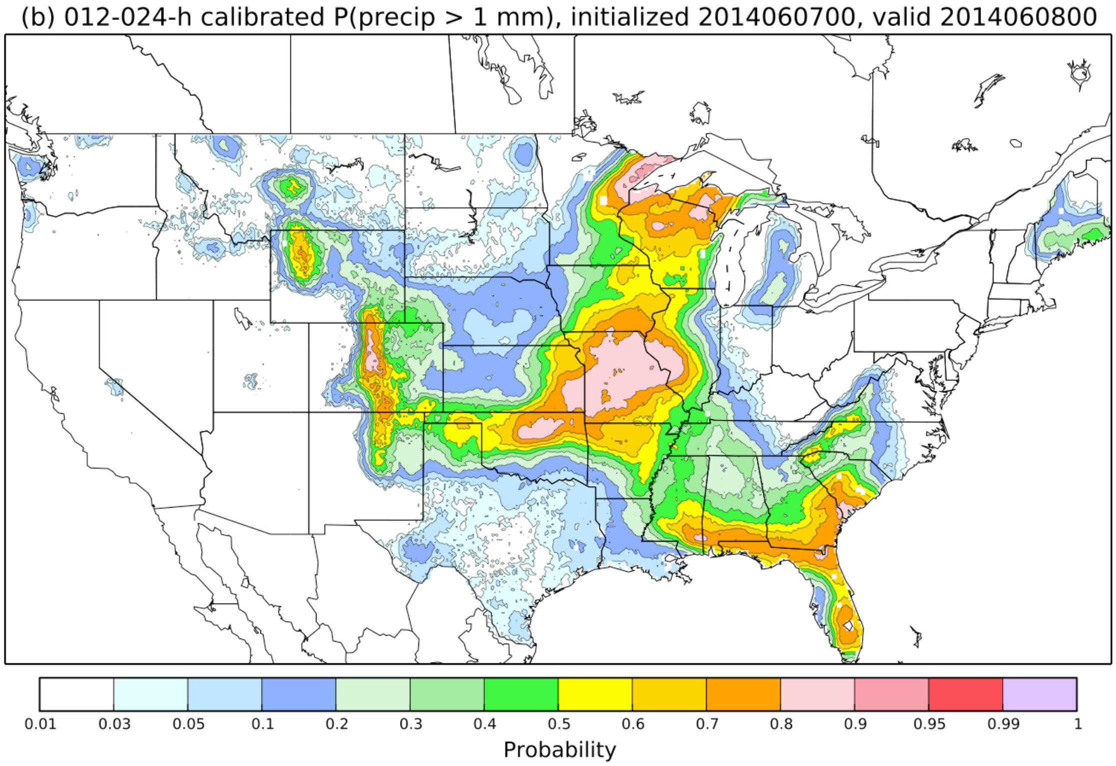

Figure A7: As in Fig. A6, but after application of Savitzky-Golay smoother with additional procedures applied along coastlines (see text).